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Influence of strain hardening on forces and contact pressure distributions in forging processes

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ABSTRACT

Purpose: The main aim of this paper is to analyze forging processes by means of the Finite Element Method (FEM) and the comparison of results with analytical methods that have been traditionally used: the Slab Method (SM) and the Homogeneous Deformation Method (HDM).
Design/methodology/approach: Both analytical methods are easier to apply than FEM but they provide less accurate results than the numerical technique. Phenomena such as the strain hardening can be easily incorporated into the Finite Element model so the influence of this factor on variables such as contact pressure distributions and platen forces can be studied.
Findings: Forces analysis shows that they are higher when strain hardening is considered. The curves of the FEM and of the SM are practically identical for the rigid perfectly plastic material. However, differences between FEM and SM are obtained for the strain hardened material. The analysis of contact pressures demonstrates that maximum pressures are always found at the center of the workpiece by SM. Otherwise, maximum pressures by FEM are located near the free surface for the lowest reductions.
Research limitations/implications: This work is a preliminary study of the influence of strain hardening on these variables. The Finite Element model that has been developed can be improved by incorporating factors such as thermal effects or models of material more complex.
Practical implications: The influence of many variables on forging process efficiency can be analysed by numerical techniques in a simple manner by means of few changes in the model.
Originality/value: Although several studies about analysis of forging processes by FEM can be found in the literature it is difficult to find a comparison between analytical and numerical results.
Keywords: Plastic forming; FEM; Forging process; Strain hardening

1. Introduction

Nowadays, processes optimization is one of the main objectives in industrial sectors. Manufacturing industries and, concretely, metal forming ones are interested in improving the quality of the final product, increasing the productivity and achieving maximum efficiency and minimum cost, consistent with the required quality standards [1-3]. An overall knowledge of the processes and an exhaustive analysis of them is required in order to reach these aims. In this sense it is important to obtain as much information as possible of what occurs in the process. Analytical methods have been traditionally used for obtaining this information [4-8] but it can be done more efficiently by the Finite Element Method (FEM). In this sense several works have been done by our research group [9-11], and by other researchers [12-18].

Forging is a metal forming process in which the workpiece is shaped by compressive forces applied through various dies and tools. Open die forging (also called upsetting) is the simplest forging process. This forging process consists of compressing a workpiece between two flat dies and reducing it in height.

In metal forming processes and therefore, in forging processes, the main contributions to the energy that is necessary to carry out the process are [19]:

Homogeneous Deformation Energy. This energy is related to the change of geometry that occurs as a consequence of the reduction process.

Friction Energy. This energy is due to the friction between the platens and the workpiece. As a result, the free surface of the deformed piece barrels.

Redundant or Distortion Energy. It causes the internal distortion of the metal to be deformed.

The analytical methods that are considered in this study are the Homogeneous Deformation Method (HDM) and the Slab Method (SM).

The HDM only takes into account the first contribution and provides a forging load estimation, which is useful in selecting the size of the required equipment to obtain the product.

The SM is based on the force equilibrium of a differential element (slab) in the deformation zone [20], and evaluates the energy due to homogeneous deformation and also the energy due to friction, but the internal distortion is not included in its analytical expression.

Both methods are basically employed for obtaining the forging load, and its application is generally limited to forging processes with simple geometries and idealized material laws. Other methods such as the Slip Lines Field also take into account the redundant energy [21].

However, FEM is the most accurate method between them. FEM is a powerful method that take into account the three contributions to the total energy and, besides, phenomena such as the strain hardening and other factors can be incorporated easily in the model [22-25]. In this work this analysis technique is going to be employed to evaluate the influence of certain parameters in the calculation of the forging load and contact pressure distributions under plane strain conditions. Therefore, the next objectives are searched:

1. To study forging processes under different operation conditions,
2. To obtain the degree of deformation of the workpiece once the process has finished,
3. To calculate the required forces under different conditions in order to achieve this deformation,
4. To evaluate contact pressure distributions at the die-workpiece interface,
5. To compare analytical methods results with those obtained by the Finite Element Method,
6. To study the influence of material strain hardening on forces and contact pressure distributions.

2. Methodology

2.1. Analytical methods

At first, rectangular billets of dimensions *b* and *h*, width and height respectively, are considered. This billet presents double symmetry, and this allows to consider a quarter of the original workpiece in the model in order to simplify the calculations (see Fig. 1).

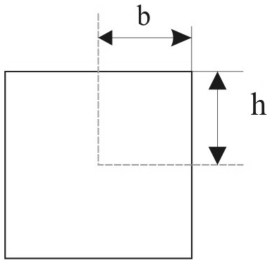


Fig. 1. Shape of the workpiece

The Homogeneous Deformation Method (HDM) only considers the required energy to develop the change of shape in the workpiece. Friction at the die-workpiece interface is not included in its analytical expresion, that can be written in a simple way. Thus, the required load for the compression of the billet is expressed by:

$$F = A_f Y \tag{1}$$

being Y the flow stress and A_f the final contact area.

The Slab Method (SM) is based on the force equilibrium of a differential element (slab) in the deformation zone [20]. Fig. 2 illustrates an example of the slab method applied to a forging process between flat platens, assuming a Coulomb friction model at the die-workpiece interface.

In this case, both the homogeneous deformation energy and the contribution of friction are considered. In order to obtain the contact pressure distributions, the forces equilibrium along the horizontal direction is done. It is supposed that the horizontal stress σ_x is uniform along the section, and besides it is one of the principal stresses together with $-p$.

Therefore, applying the equilibrium:

$$(\sigma_x - d\sigma_x)\cdot h - \sigma_x \cdot h - 2\cdot\mu\cdot p\cdot dx = 0 \tag{2}$$

$$h\cdot d\sigma_x - 2\cdot\mu\cdot p\cdot dx = 0 \tag{3}$$

Because of σ_x and $-p$ are main stresses, and the process is developed under plain strain conditions, both variables are related by means of the yield condition:

$$\sigma_1 - \sigma_3 = S \tag{4}$$

$$\sigma_1 = \sigma_x \quad ; \quad \sigma_3 = -p \Rightarrow \sigma_x + p = S = 2k \tag{5}$$

where k is the shear yield stress, and Y is the yield stress.

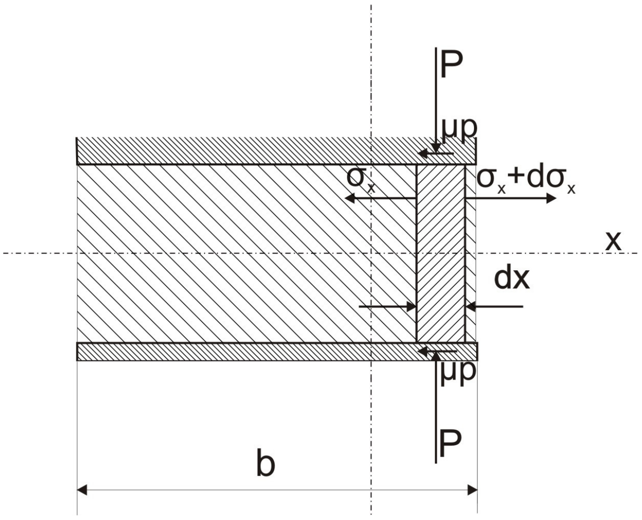


Fig. 2. Stresses in a differential element of the workpiece for a plane strain forging process

Replacing eq. (6) in eq. (4) and considering that the constant of integration is calculated from the condition that the horizontal stress is null in both extremes, the following expression is obtained:

$$\frac{p}{2k}=e^{\frac{2\cdot\mu}{h}\cdot\left(\frac{b}{2}-x\right)} \qquad (6)$$

It can be observed that eq. (7) is an exponential function that increases from a value $p = 2k$ in the extremes until a maximum value in the center of the workpiece:

$$\left(\frac{p}{2k}\right)_{\max}=e^{\frac{\mu\cdot b}{h}} \qquad (7)$$

An approximation of this function to a straight line can be done when friction is small, obtaining in this case the maximum value:

$$\left(\frac{p}{2k}\right)_{\max}\approx 1+\mu\cdot\frac{b}{h} \qquad (8)$$

Therefore the equation for contact pressure distributions can be written in the following way:

$$\frac{p}{2k}=1+\frac{2\cdot\mu}{h}\cdot\left(\frac{b}{2}-x\right) \qquad (9)$$

In the forging process, the shape of the billet changes continuously during the operation and therefore, contact pressures change as well.

The value of the contact pressures can be calculated at any point by means of eq. (7). Otherwise, the forging load can be obtained from the calculations of pressures: the integration of the equation (7) on the workpiece - platen contact surface, taking into account the volume constancy relation leads to:

$$\frac{F}{S}=-\frac{h\cdot w}{\mu}\cdot\left[e^{\frac{\mu\cdot b_i\cdot h_i}{h_f^2}}-1\right] \qquad (10)$$

2.2. Finite Element Method

A general purpose code has been used for developing this analysis. ABAQUS/Standard is a finite element code of implicit methodology [26]. The element type of the mesh is CPE4R and consists of a continuous, plane strain, 4-node and reduced integration element with hourglass control (see Fig. 3) [27].

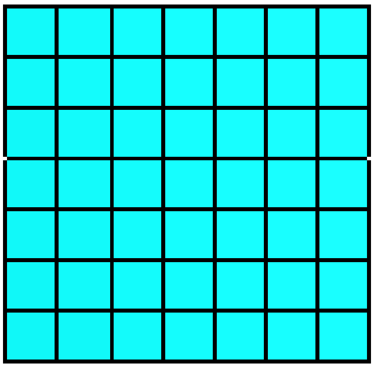


Fig. 3. Mesh of the workpiece

In this study, it has been chosen a workpiece with a base to height ratio $b/h = 1$, where $h = 1$, therefore a square shape is considered. On the other hand, a Coulomb friction coefficient of 0,1 has been assumed. The reduction in height is defined as $(h_i-h_f)/h_i$, where $h_i = h$ and $h_f = b$. In this sense, three values of the reduction are analysed: $r = 5\%$, $r = 25\%$ and $r = 50\ \%$. Forces have been expressed in terms of the dimensionless ratio $F/(A_i\ S)$, where A_i is the initial contact area, and $S = 2k$ is the yield stress under plane strain conditions. Contact pressures are represented in an absolute scale. Regarding the material, the billet has been modeled with an aluminium alloy, and two material behaviour are supossed: a rigid perfectly plastic material, and a strain hardened one.

3. Results

Figure 4 presents the predicted forces in an adimensional way for the Homogeneous Deformation Method (HDM), eq. (1), for the Slab Method (SM), eq. (11), and for the Finite Element Method (FEM), for the three reductions (5%, 25% and 50%). Fig. 4a) shows the results for a rigid perfectly plastic material, and Fig. 4b) for a strain hardened one.

It is observed that forging loads are higher when strain hardening is considered. The curves of the FEM and of the SM are practically identical for the rigid perfectly plastic material.

However, the differences between both curves increase gradually with the displacement of the platens for the strain hardened material. The HDM provides a lower limit of the forging load in both cases.

Otherwise, contact pressure distributions for both material behaviours are observed in Fig. 5 and 6. In these figures the distributions that have been obtained by the Slab Method are presented, considering an exponential (6) and a lineal (9) expression of the contact pressures. Differences between them are more significant for the highest reduction (50%), while there is no important differences for lower reductions. Also FEM results are shown.

For both materials it is observed that FEM results remain above the values of SM, because finite element models allow to consider phenomena such as strain hardening and also they take into account the distortion energy of the process. Although FEM provides more accurate solutions, SM gives acceptable results and it can be applied in a simple manner.

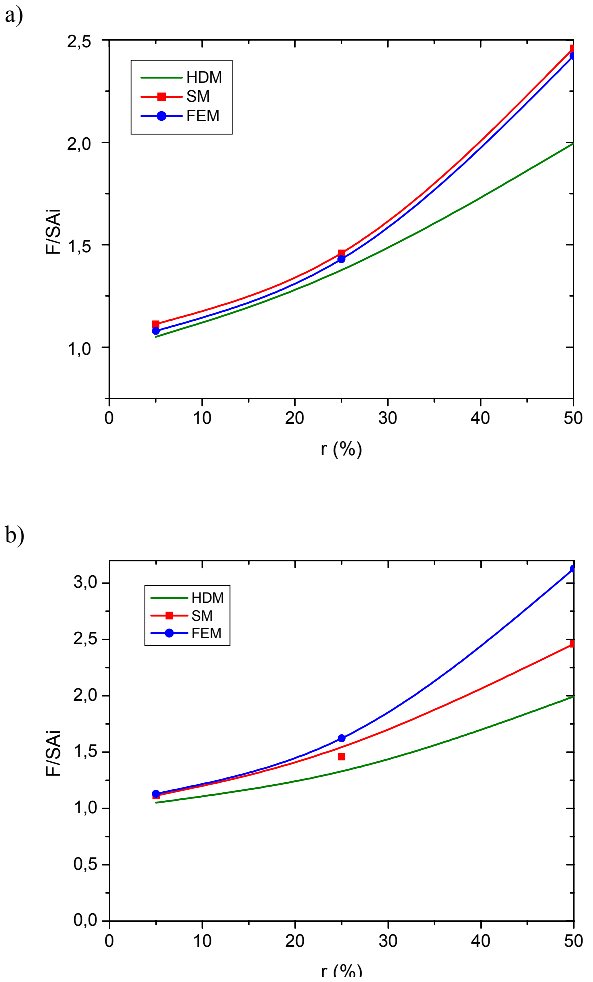


Fig. 4. Prediction of compression forces for different displacements of the platens. a) rigid perfectly plastic material; b) strain hardening material

The behaviour that is observed at the right hand of the FEM graphics is due to folding fenomena. The free surface folds when contact with the platens occurs and this is a known problem when simulating forging processes by FEM.

In Slab Method, the maximum pressures are always found at the center of the workpiece. Otherwise, in FEM, maximum pressures are located at the free surface side for the reductions of 5% and 25%. However, a similar trend than for SM is observed for the highest reduction, 50%.

In these graphics, the influence of the material model on the contact pressures is also shown. Both types of material have practically the same behavior, although the pressure values are higher for the strain hardened one. This conclusion can only be extracted from the analysis by FEM that shows that contact pressure increases when strain hardening is considered. Analytical methods such as SM do not reproduce this phenomenon.

On the other hand, FEM allows to obtain stress diagrams that show the results in a graphic way, as it can be seen in Fig. 7 and 8. In these graphics equivalent stresses are represented for a rigid perfectly plastic material (Fig. 7) and for a strain hardened one (Fig. 8), considering the three reductions, 5%, 25% and 50%.

Also, strain diagramas are represented (Fig. 9 and 10). These figures show equivalent strains both for a rigid perfectly plastic material (Fig. 9) and for a strain hardened one (Fig. 10), considering the three reductions, 5%, 25% and 50%.

4. Conclusions

In the present work, forging processes have been analysed under plane strain conditions. Forces and contact pressure distributions have been obtained for different values of the reduction of the billet, considering both a rigid perfectly plastic material and a strain hardened one.

In this sense, different analysis methods have been employed: two analytical methods (Homogeneous Deformation Method and Slab Method), and a numerical method (Finite Element Method). Results have been compared between them.

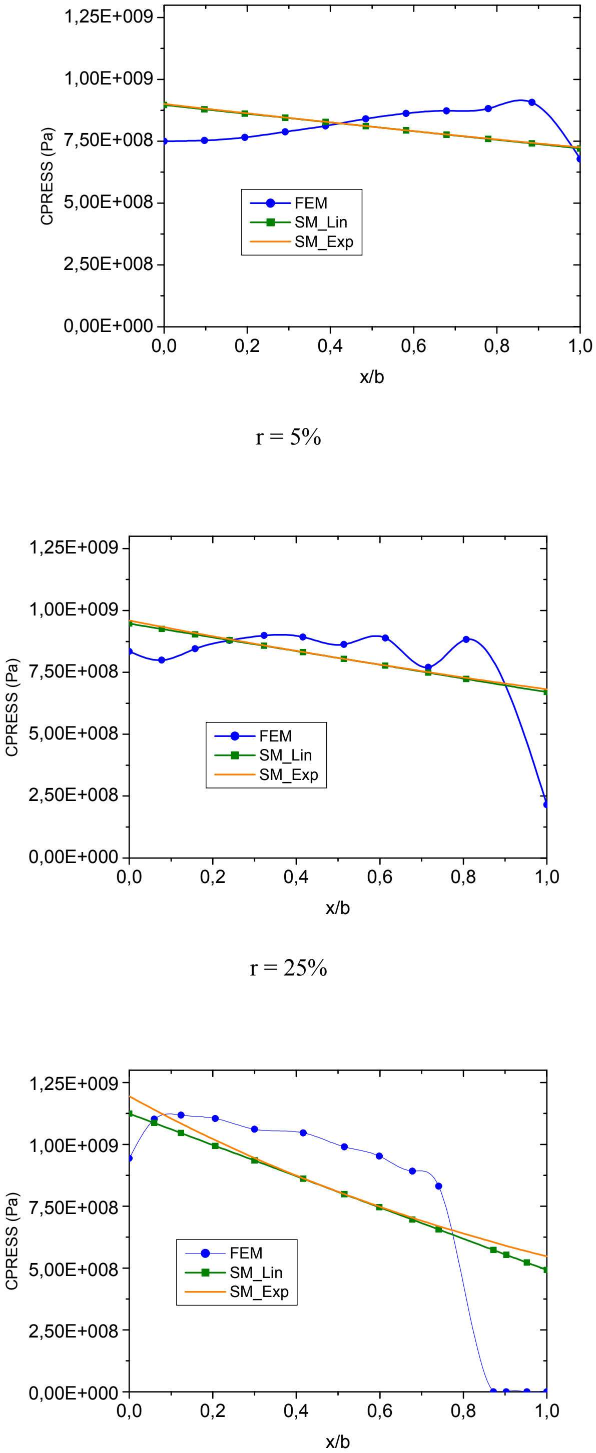
Forces analysis shows that they are higher when strain hardening is considered. The curves of the FEM and of the SM are practically identical for the rigid perfectly plastic material.

However, differences between FEM and SM are obtained for the strain hardened material. The HDM provides a lower limit of the forging load in both cases.

The analysis of contact pressures demonstrates that maximum pressures are always found at the center of the workpiece, by Slab Method. Otherwise, maximum pressures by FEM are located near the free surface for the lowest reductions. However, a similar trend than for SM is observed for the highest reduction, 50%.

The influence of the material model on the contact pressures shows that both types of material have practically the same behavior, although the pressure values are higher for the strain hardened one.

Although FEM provides more accurate solutions, it can be concluded that SM gives acceptable results and it can be applied more easily. However, the influence of the material behaviour can only be studied by a powerful method such as FEM.

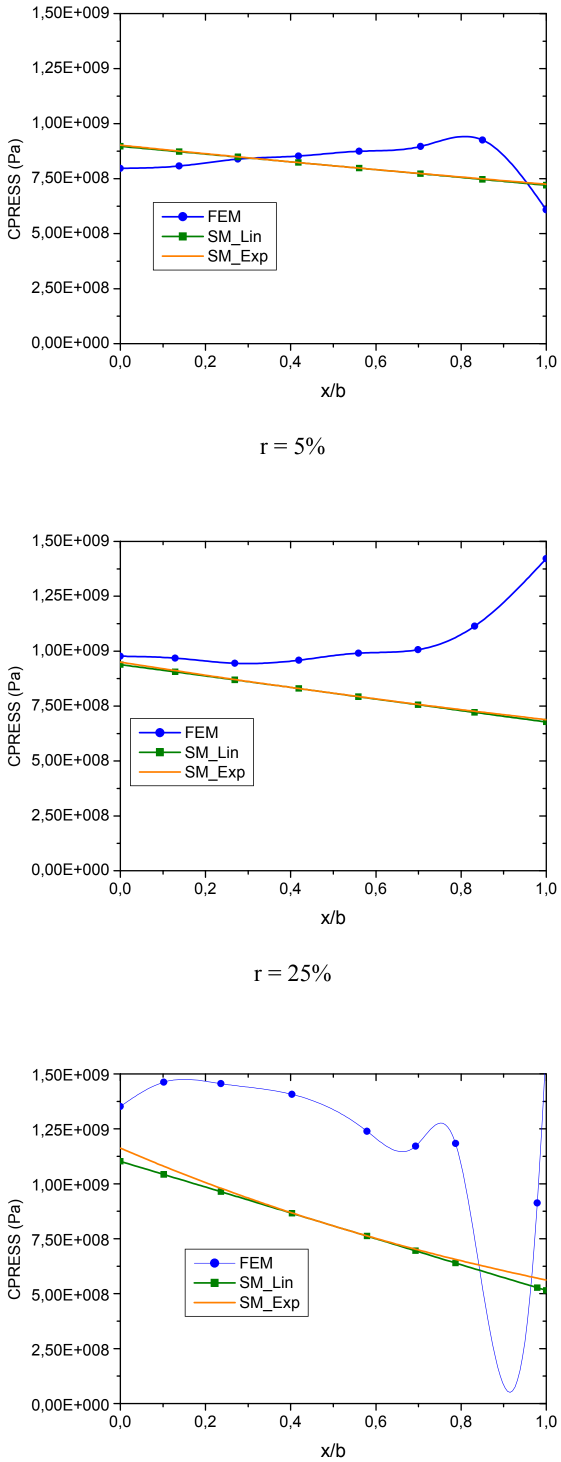


r = 5%

r = 25%

r = 50%

Fig. 5. Contact pressure distributions for a rigid prefectly plastic material

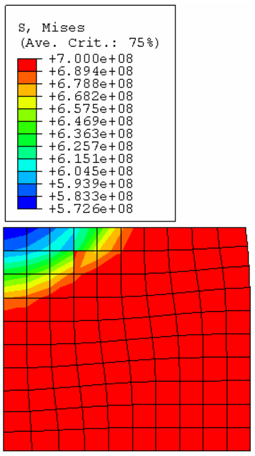


r = 5%

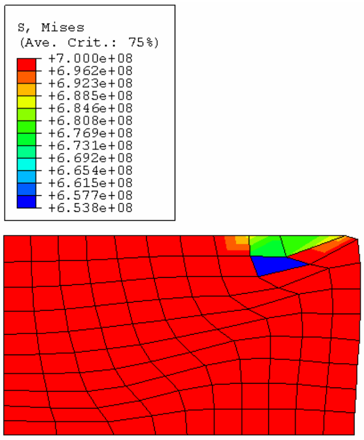
r = 25%

r = 50%

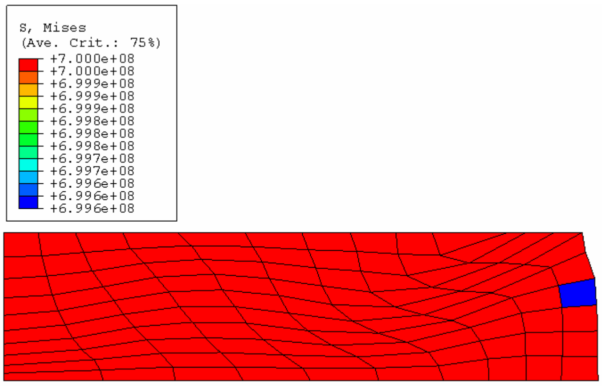
Fig. 6. Contact pressure distributions for a strain hardened material



r = 5%

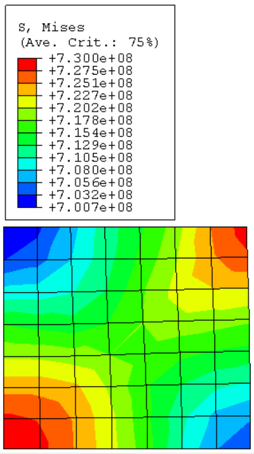


r = 25%

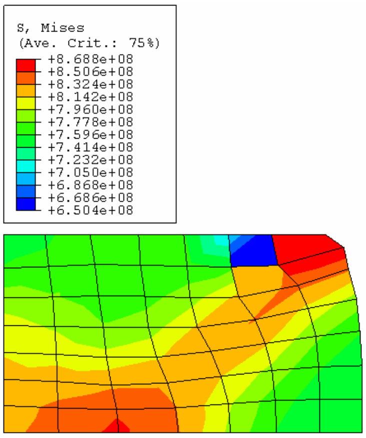


r =50%

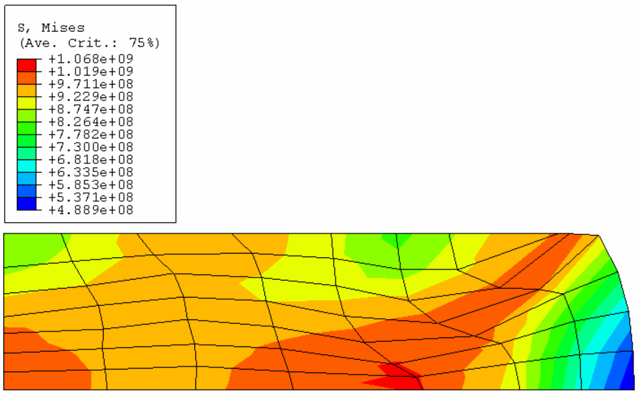
Fig. 7. Equivalent stresses for a rigid perfectly plastic material with a base to height ratio b/h=1, μ=0,1 and the three values of reduction



r = 5%

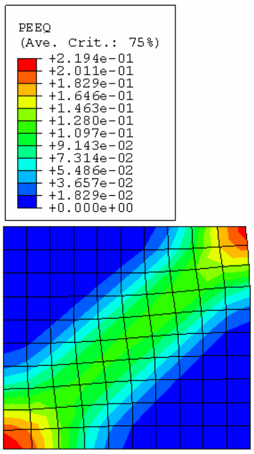


r = 25%

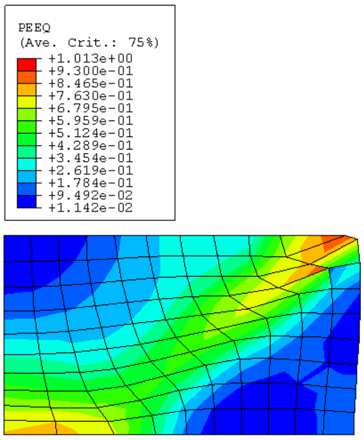


r =50%

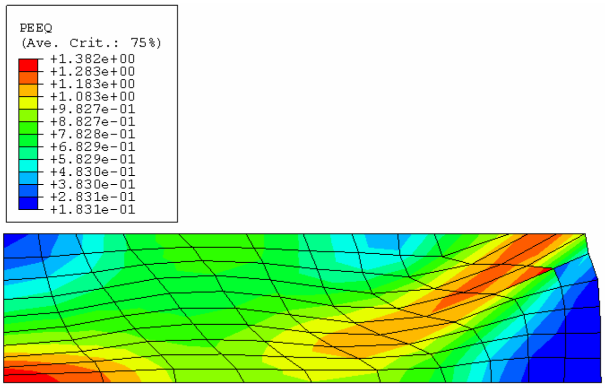
Fig. 8. Equivalent stresses for a strain hardened material with a base to height ratio b/h=1, μ=0,1 and the three values of reduction



r = 5%

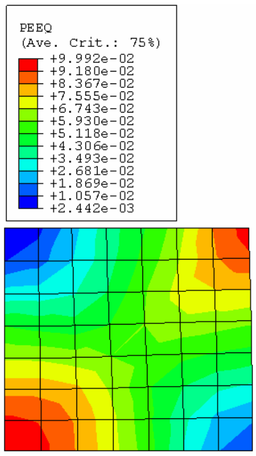


r = 25%

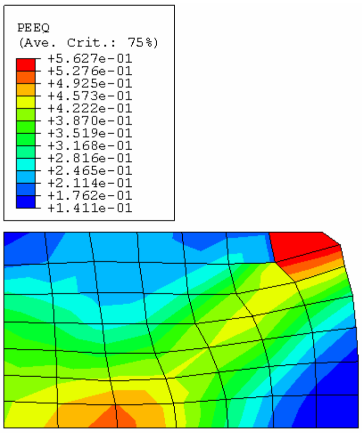


r =50%

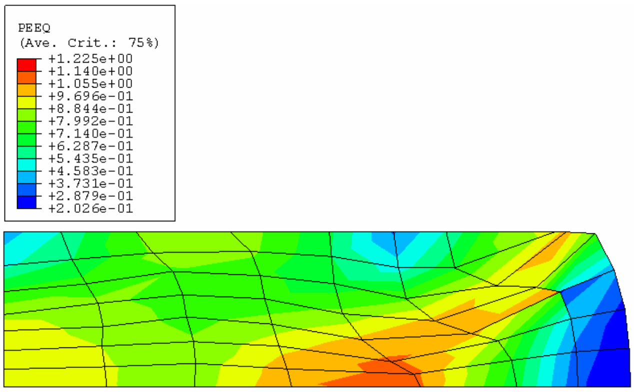
Fig. 9. Equivalent strains for a rigid perfectly plastic material with a base to height ratio b/h=1, μ=0,1 and the three values of reduction



r = 5%



r = 25%



r =50%

Fig. 10. Equivalent strains for a strain hardened material with a base to height ratio b/h=1, μ=0,1 and the three values of reduction

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